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The Advanced Fuel Cycle Initiative

"Science-Based" Approach to Transmutation Fuel Development

Douglas L. Porter

From a recent presentation by
Kemal O. Pasamehmetoglu
Transmutation Fuels Campaign Director

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Presentation Contents

- Campaign Mission and Objectives (Old and New!)
- Campaign "Science-Based" Implementation Strategy
- Campaign Grand Challenges
- Execution Strategy
- M&S Needs and Interfaces

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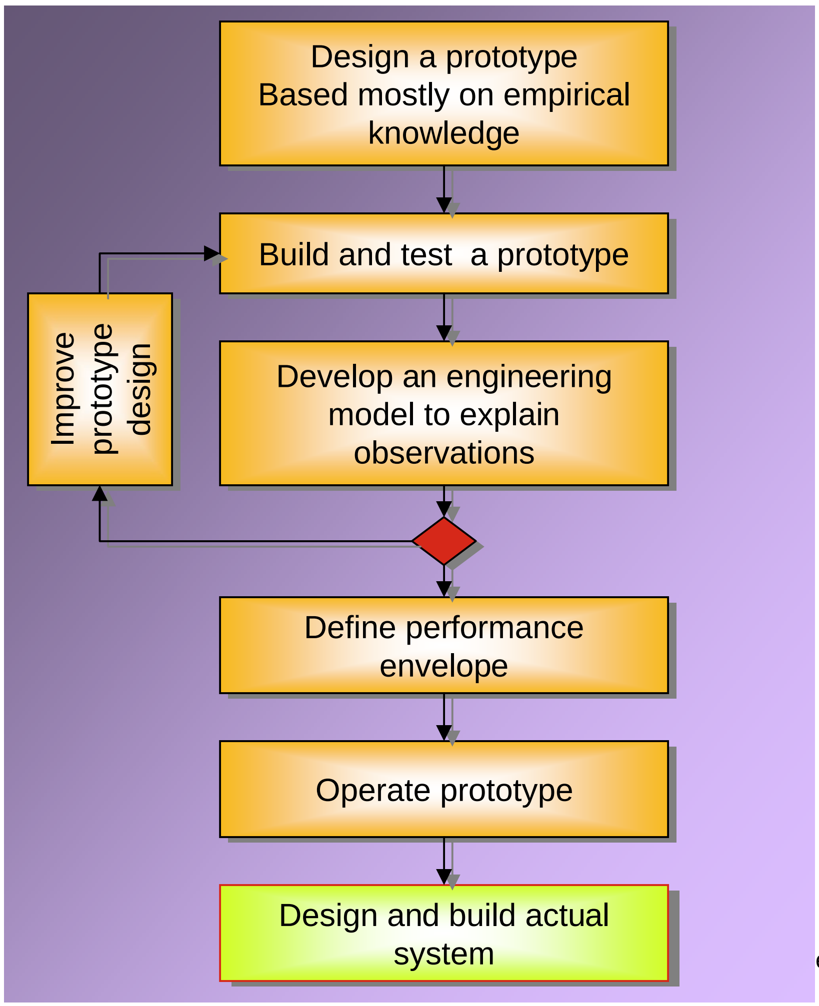
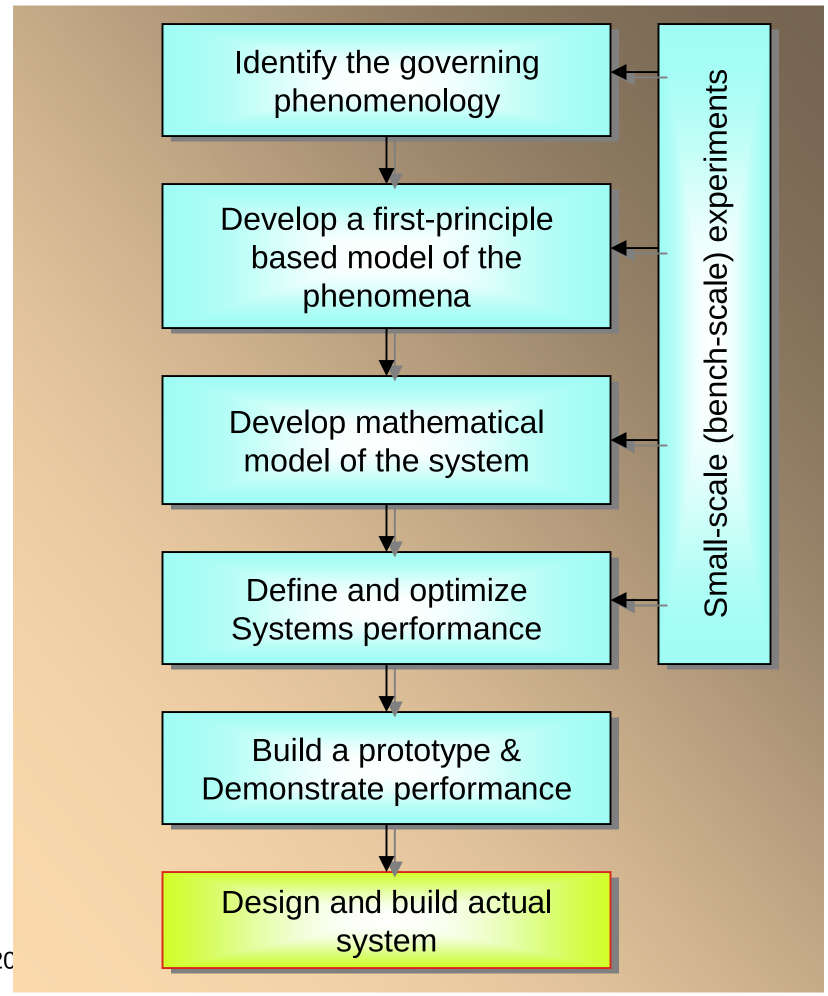
Prototype-Based vs. Science-Based Approaches

Engineering Approach
Empirical - Observational



"Science-Based" Approach
Predictive



Mission and Objective (OLD)

- The Mission of the Transmutation Fuel Campaign (TFC) is to perform research development and demonstration (RD&D) activities leading to the generation of data, methods and models to demonstrate fast reactor transmutation fuels/targets fabrication process and performance envelopes.

- The 20-year Objective of the TFC is to complete the qualification of an initial form of transmutation fuel/target for use in fast burner reactors over the entire range of compositions to obtain closure of the fuel cycle while maintaining the commercial competitiveness for nuclear energy.

  The success of meeting the objective is heavily dependent on the scientific explanation of the observed fuel behavior.

- *Qualification means demonstration that the fuel will perform predictably and acceptably under normal operations and transient conditions. This will be achieved by targeted testing and advanced modeling and simulation.*

Mission and Objective (NEW)

- The Mission of the Transmutation Fuel Campaign (TFC) is to perform research and development (R&D) activities on fuel system's behavior under irradiation and fabrication processes to achieve multi-fold improvements for in-pile performance and process efficiency.

- The 20-year Objective of the TFC is to complete a micro-structural design of fuel systems (fuel + cladding) that can achieve very strict fabrication process and in-pile performance requirements.

  The success of meeting the objective is heavily dependent on the fundamental models (experimental & theoretical) that allow prediction of critical phenomena and their impact on fuel performance..

- *Micro-structural design means being able to engineers the microstructure of homogeneous or composite fuels with strategically located additives to achieve the defined performance objectives.*

Revised Functions & Requirements

TFC Mission

The technical management of the R&D activities is gauged to TRL concept.

TFC Interface Functions & Requirements

OPTIONS

- *Compositions*
- *Feedstock chemical & mechanical specs*
- *Discharge burnup*
- *Linear power*
- *Clad temperature*
- *Clad breach fraction*
- *Fabrication losses*
- *Waste forms*
- *Fabrication cost*
- *Geometry*

TFC Integration Functions & Requirements

- *Fabrication*
  - *Feedstock*
  - *Pellets/Slugs*
  - *Process Theory*
  - *Innovative Process Design*
  - *Detailed Characterization During testing*
  - *M&S*
- *Performance*
  - *Out-of-Pile Testing*
  - *In-Pile Testing (SS, TR)*
  - *Detailed Characterization*
  - *In-pile measurements*
  - *Closure of Meso-scale theory*
  - *M&S*

TFC Products

- *Fuel design at the microstructure level tailored to performance requirements.*
- *Process design tailored to requirements*

Possible Grand-Challenges

- *Develop ultra-high burnup fuels (≥ 400 MWd/kgHM) for fast reactors.*
  - this challenge will almost certainly require development of advanced cladding alloys or composites and will possibly require innovative assembly design.
  - Fuel failure fraction target: near zero (10^{-6} ??).

- *Develop highly reliable, repeatable, efficient and affordable fabrication processes with < 0.1% irretrievable TRU losses and < 1% reject/scrap rate.*

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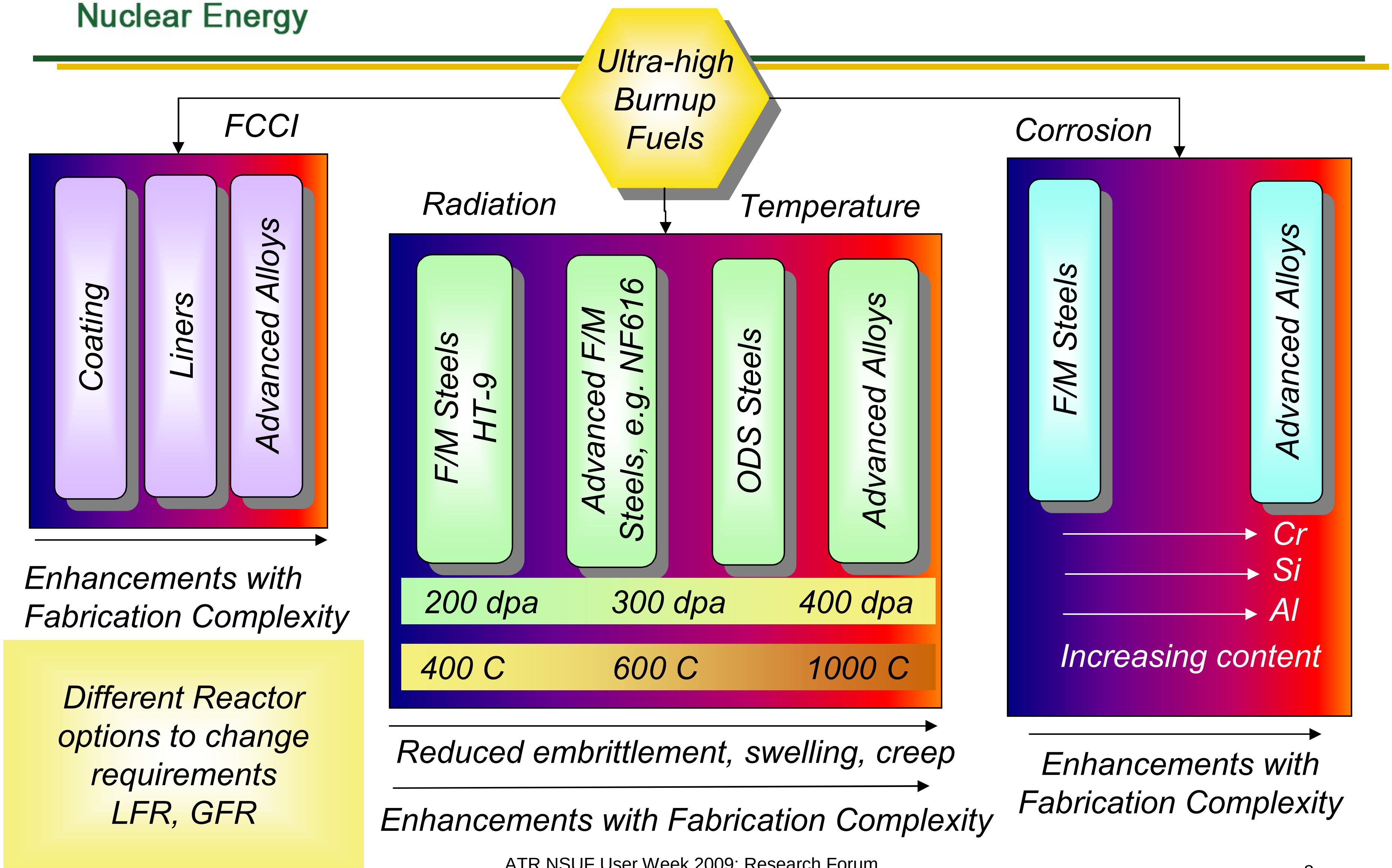
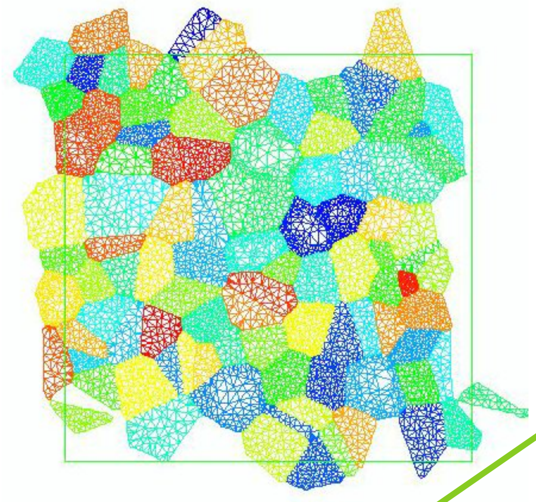
Advances in Cladding Materials



For the first 5-years, focus will be on mesoscale understanding of fuels and cladding materials



Integrated Mesoscale Model

Combined phase-field & FEM approach captures concurrent microstructure formation and evolution in alloy and oxide fuels under irradiation, temperature and stress

Theory

Comprehensive crystal phase-field (Cahn-Hilliard & Allen-Cahn) equations for

irradiation effects (fission-gas behavior, void swelling,…)
alloy species redistribution, phase behavior & off-stoichiometry (in oxides)
effects of stress and temp. gradients

Model calibration & validation

Experiments

Characterization of microstructure formation & evolution:

- fission-gas and void-swelling behavior
diffusion coefficients (incl. thermo-migration and stress gradients)
species redistribution (segregation, precipitation, …), elastic moduli, …

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Activities to support the revised functions and requirements

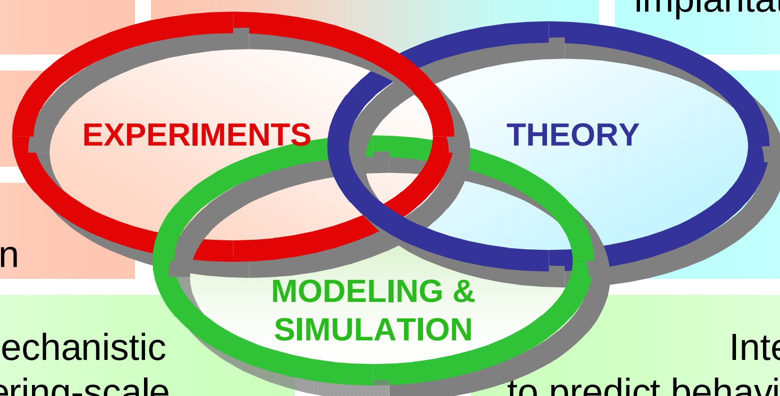
- In-pile measurements aimed at isolated phenomenology with instrumentation.
  - Development advanced in-pile instrumentation.
- Out-of-pile testing
- Characterization methods at micro-scale
  - Characterization equipment development (emphasis on hot samples)

Design of targeted in-pile and out-of-pile experiments guided by the theory and the needs of the closure models.

Design of scalable bench-scale fabrication tests with instrumentation

Micro-structural description of the fuel and cladding:
-Closure of combined transport and phase-field equations
-Separate effect testing and properties measurement needs at sub-grain scale.
-Interpretation of results at multi-grain, multi-phase scale
-Effect of nano-scale implantations

Detailed characterization of feedstock properties ★



★ Understanding of feedstock effects on the product quality

Small-scale fabrication tests with enhanced instrumentation

Fabrication techniques for controlling microstructure

Fabrication simulator using mechanistic models to scale up to engineering-scale applications

Integral fuel-performance code to predict behavior at assembly-scale during steady-state and transient conditions.

★ *Interface with separations campaign*

MODELING & SIMULATION NEEDS

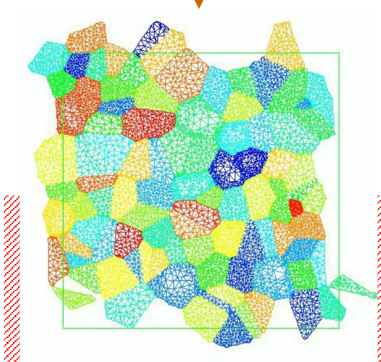
Modeling & Simulation Function and Requirements

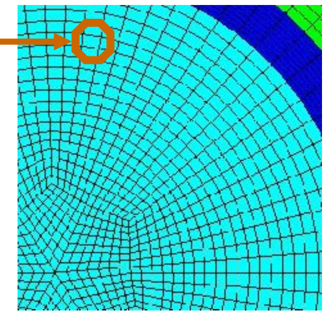
- **The M&S products will be used to**
  - Fuel formulation/design and fabrication process design
  - Design of experiments and analysis of irradiation performance
  - Licensing (fuel safety basis).

Fabrication and Performance Code High-Level Requirements

- The suite of codes for fuel fabrication and performance shall
  - predict the fuel element safety margin during normal reactor operation and design-basis accidents
  - predict the time at which a fuel-element-cladding breach will occur
  - support the fundamental understanding of fuel-element's behavior during irradiation
  - aid the fuel-elements design (micro-scale & engineering designs) for optimal performance
  - aid the fuel and clad fabrication process design to achieve the desired fresh fuel properties

Mesoscale to continuum mechanics bridging should be the near term focus





Continuum Mechanics (IPSC)

Scale bridging

Numerical Solution Of Unified Mesoscale Model
- 3d solution of phase-field and FEM equations

Unified Mesoscale Model
Combined phase-field & transport theory

Theory
Comprehensive crystal phase-field (Cahn-Hilliard & Allen-Cahn) equations.

Experiments
Characterization of microstructure formation & evolution, measurements of crystal properties

Scale bridging

Electronic Structure, Molecular Dynamics, KMC